

**BUILD AND TEST A NEW TYPE OF COMPRESSOR  
FOR STRIPPER WELL PRODUCTION APPLICATION  
FINAL TECHNICAL REPORT**

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**PAUL WEATHERBEE, PRINCIPAL AUTHOR  
W&W VACUUM & COMPRESSORS, INC.**

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## **ABSTRACT**

**The research and development project goal is to evaluate the Weatherbee compressor concept via prototyping and testing in a controlled environment. Specifically:**

- 1.     Task 1 of the project requires re-engineering the existing 8.5 inch pump design into a 4.0 inch compressor version with two seal configurations. One configuration features fluid seal and the other features mechanical seal, which had to be designed, for operation with minimal lubrication.**
- 2.     Task 2 of the project requires construction of two prototype compressors in order to establish baseline operating characteristics and performance and to specifically evaluate seal designs. During the performance of this task we designed 3D computer models which were, and will continue to be, extensively utilized.**
- 3.     Task 3 of the project requires bench testing of prototype compressor systems.**

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## **EXPERIMENTAL**

Task 1 and Task 2 discussed in detail in the **RESULTS AND DISCUSSIONS** section of this report provide extensive information relative to the experimental nature of this project. The experimental aspects of the test bench are discussed below.

The custom compressor test bench described in Task 3 is the cornerstone for compressor experimental testing. Further details of the test bench are as follows:

1. Heavy steel construction for vibration absorption and for a rigid coupling environment;
2. Ten horsepower drive motor;
3. Closed loop dry sump lubrication system for both oil intake injection and internal lubrication;
4. Intake vacuum monitoring;
5. Intake/exhaust temperature monitoring (4 ports);
6. Combined exhaust flow rate, including downstream temperatures, pressures and flowrate;
7. Custom oil/air separator with oil return line to dry sump system;
8. Exhaust pressure monitoring;
9. Programmable digital compressor motor control; and
10. Heavy duty high misalignment stainless steel drive coupling.

The test bench will accommodate all current versions of the four inch compressor, as well as future versions up to approximately 5 inches.

Compressor testing is conducted via conventional experimental methods for similar machinery. Specifically, compressor rpm is established in a steady-state environment or via a programmed performance cycle featuring a range of shaft speeds. Intake suction is measured. Similarly, exhaust temperature is measured very near each compressor chamber exhaust port. Type T thermocouples are utilized. Downstream of the exhaust manifold, where both compressor chamber exhaust hose merge, flow is measured with a conventional turbine flowmeter with standard atmosphere compensation. Pressure and temperature is also measured nearby the flowmeter. This apparatus, in total, allows for rapid and repeatable compressor performance characterization.

Finally, as mentioned in Task 3, experimental testing activity to date has considered mechanical survival of prototype components only. There has not been any significant compressor performance characterization, although we are confident that the test apparatus is well designed and prepared, and will allow compressor evaluation upon initiation of our next round of activity.

## **RESULTS AND DISCUSSIONS**

### **Task 1:**

**The first activity required selection and qualification of an engineering and manufacturing facility that would work closely with W&W to re-engineer the preexisting 8.5 inch pump, and formalize the new 4.0 inch configurations. This project requires a high quality manufacturer with a strict design and quality control system. Moreover, the selected manufacturer must be capable of maintaining very close dimensional tolerances and be capable of manufacturing complex component geometries. Another essential feature of the selected manufacturer must be their ability to effectively use three-dimensional design software such as SolidWorks.**

**Over ten different facilities were considered: two in the Dallas-Fort Worth area, one in Eastland, Texas, one in Brownwood, Texas, and six in the Austin area. The selection process included meetings with company owners, engineers, quality control specialists and manufacturing specialists. Business references and experience with similar projects were also considered.**

**Thereafter, W&W selected Athena Manufacturing, LP, located in Austin, Texas. Not only does Athena have a state-of-the art facility but they are also ISO 9001:2000 compliant and expect registration in December 2004. They have a highly skilled engineering staff, as well as a core group of highly skilled machining experts who are proficient in all phases of modern computer-based machining technology.**

**Athena's quality management system requires thorough work instructions for every component, followed by dimensional and cosmetic inspection throughout each step of the manufacturing process. Permanent records of such inspections are kept for future reference and traceability. Athena's facility is temperature controlled, and their inspection personnel use extremely accurate three-dimensional measuring equipment. W&W has been more than pleased with the quality of the workmanship provided by Athena.**

**After selection of the manufacturing facility, W&W, along with Athena engineers, began the engineering process whereby the original 8.5 inch pump mechanical drawings were converted into a three-dimensional computer-aided-design (CAD) electronic format. The engineering software package SolidWorks was selected due to its widespread use and parametric capabilities. SolidWorks CAD models and drawings can be electronically reprocessed for any spherical diameter, and subsequent design changes do not require manual regeneration of every compressor component drawing, resulting in a substantial efficiency gain during the evolution of this family of products. As our R&D efforts progress we will benefit greatly from this initial, time-consuming 3-D CAD model preparation effort.**

**During this engineering phase of the project, two separate configurations of pump sealing**

methodologies were selected, one fluid-based and one mechanical-based. The fluid seal system will require oil injection into the compressor intake stream as well as an internal re-circulating bearing oil system. The mechanical system will feature the same re-circulating oil system, but will feature face, lip and/or gland seals between the vanes and housing, thereby eliminating the need to inject oil into the compressor intake stream.

Specifically, the four compressor locations that we considered sealing are: (1) between the carrier ring and stationary shaft; (2) between the vanes and the housing; (3) between the vanes and the stationary ball; and (4) between the vane-to-vane overlap.

The fluid-based seal system achieves compressor chamber sealing hydrodynamically. A precision controlled lubricator apparatus injects oil into the compressor intake stream, much like a system employed in rotary screw devices. Initial testing during Task 3, described in detail below, proved that without location (1) seals excessive oil from the re-circulating oil system entered the compressor chambers resulting in fluid locking and mechanical damage, therefore the fluid-based seal system will feature location (1) seals similar or identical to the mechanical-based configuration. This seal must be located in the (1) seal area between the carrier ring and stationary shaft. Two different seals, each with a different material, were tried and failed; the details regarding these failures are discussed below.

For both seal configurations, W&W solicited seal design assistance from several seal manufacturing vendors. Specifically, we met with Parker-Hannifin design engineers in both Abilene and Austin to inspect the pump, review the 3-D CAD models and conduct engineering discussions. We had multiple meetings with Boeing engineers in Houston, including detailed evaluation of the 3-D CAD data. We also had multiple meetings in Shiner, Texas and Austin with Boedeker Plastics representatives. Many other prospective seal vendors and consultants were researched and considered. The substantial time consumed with soliciting seal configuration advice and suggestions from recognized industry experts greatly accelerated our compressor seal design cycle, and established a broad knowledge base on which we will rely on heavily going forward.

Several seal designs were identified for potential use in the mechanical-based seal configuration. One is a Parker-Hannifin design. This polymeric seal is molded from a liquid-filled polyurethane and features an energized design to impart continual pressure between the vanes and housing. This seal will be used in locations (2), (3) and (4) listed above. Parker-Hannifin engineers in Houston, Dallas and Salt Lake City participated in this design effort.

Another design for the mechanical-based system was for use in location (1), between the carrier ring and stationary shaft. The location (1) seal is critical in that it must be present to prevent excess oil from getting into the pump. After extensive research and with assistance from both DuPont and Boedeker Plastics engineers, the engineered polymer Radel was selected based on its widespread application in oilfield applications, as well as its low water absorption

and thermal expansion coefficients. As a contingency, we also selected the engineered polymer Delrin (acetal copolymer) for this seal design. Both materials (Radel and Delrin) were used and under test conditions, both failed. Although we were assured that neither of these materials would “swell” when they were put under “load” (heat and oil), they both failed when tested.

W&W has worked with Boeing’s Engineers to develop the most recent seal design considered for the mechanical-based system (this is the third seal designed for the (1) location).. This energized type seal is also for use in location (1), and features a spring-loaded carbon composite seal element housed in a stainless steel ring. We believe this configuration has the flexibility to withstand the “load pressures” which will be encountered in seal location (1).

## **Task 2:**

After approval of the compressor design, including the two seal configurations the process of machining and assembling the prototype compressors began. Due to the complexity of many of the components, and the very close dimensional tolerance requirements between moving components, there was a steep learning curve on the shop floor. While this learning curve caused some delays, W&W remained focused on the project requirements.

Each component and subassembly was assembled, checked, adjusted and rechecked numerous times in order to achieve the required component interrelationships. As is the case with all new product development, actual hands-on activities establish the accuracy and suitability of the computer-based design, while simultaneously uncovering design errors and/or shortcomings. For example, one problem we encountered was due to tolerance stack-up in a particular subassembly, which SolidWorks did not predict. Several instances of this nature occurred resulting in component redesign and subsequent remanufacture. The manufacturing process generated a significant collection of nonconforming and/or obsolete pump components, representing a substantial investment of both time and money.

A total of five compressors were built. Compressor housings were manufactured in heat-treated alloy steel, cast iron, and acrylic polyurethane. Compressor vanes and shafts were manufactured in heat-treated alloy steel and 17-4 PH stainless. A wide variety of bearing types and assembly configurations were evaluated. Painstaking efforts were undertaken to achieve the closest dimensional tolerances of the shaft/vane subassembly without sacrificing future manufacturability.

We currently have compressors running smoothly, after overcoming some initial problems always associated with resizing and implementing a new design; i.e., vibration, knocking and metal-to-metal contact.

### **Task 3:**

Task 2 and Task 3 occurred simultaneously – as soon as a complete compressor was manufactured it was tested. Thereafter, after the next sequence of design and/or manufacturing revisions were complete another round of testing transpired. In the near future, and when the compressor design stabilizes, much more formalized bench and field testing will occur, especially with seal development.

Each compressor was bench tested using a custom test bench. The test bench features a 10.0 horsepower synchronous AC motor with a programmable digital controller. This arrangement allows specification of precise RPM and/or shaft power thereby allowing highly repeatable compressor input conditions. The test bench also features a self-contained re-circulating oil system for use with both the fluid and mechanical compressor seal configurations.

Needless to say, the bench testing revealed a substantial amount of information, often times in the form of a post-failure analysis. Initially, the bench testing served simply as a mechanism to conduct reliability testing. We simply need to achieve prolonged compressor operation, regardless of performance, without suffering a mechanical failure. Thereafter, as we established reliability via design and manufacturing process evolution, we began focusing on performance and data collection.

Due to the time and costs associated with successfully manufacturing an operational prototype while simultaneously designing and developing two compressor seal configurations, we have depleted Phase I funding, and the continuation of Task 3 will shift to Phase II funding. Specifically, we expect the Boeing face seals (location 1) to be successful, thereby allowing finalization of the fluid-based seal configuration, as well as subsequent implementation of the Parker vane seals to finalize the mechanical-based seal system.

### **Confidential and Proprietary Information Regarding Task 3:**

During Task 3 activities, it became apparent that the compressor housing port (suction and discharge) design was not optimized. Specifically, the original design caused re-compressing due to an inordinate port overlap inherent to the timing of the compressor. This caused substantial extra work and associated heat generation, while substantially degrading the output pressure capability. It was determined that we needed to both reshape and relocate the ports and by using the 3D Computer Model were able to accomplish this task.

We approached this redesign activity with a goal of achieving a 3:1 compression ratio. This design change has been completed, and also features the capability to further throttle the compressor with simple intake port inserts which should allow inexpensive compressor configuration for any specific wellhead condition. We expect this ability to easily configure



**a compressor for any desired compression ratio by simply changing an insert will represent a giant leap for this family of products by providing a wonderful level of versatility.**

**Upon initiation of Phase II funding all Task 3 testing activities will be based on this new port design.**

## **Financial Report**

**Under this grant, W&W Vacuum & Compressors, Inc. received an award of \$100,000.00 for Building and Testing a New Type of Compressor for Stripper Well Production Application”, with a cost share commitment from W&W of \$50,000.00. W&W requested reimbursement from the Stripper Well Consortium a total of \$100,000 and contributed (cash and in-kind) a total of \$81,025.00.**

## **Conclusion:**

At the end of Task 1 activity, the design of the four inch unit for stripper well use was completed. It was identified early on that the design of the seals between the rotating and stationary components would be a driver in successful operation of this unit. Therefore, considerable effort was spent meeting and working with various seal OEM's. Most notably, the services of Parker Hannifin were employed to provide an energized contacting polymer seal design to be used between the vanes and the stationary components. It was also recommended that a simple o-ring type seal between the carrier ring and the center ball stationary shaft be used.

The goal in Task 2 was to draw the compressor in 3-D modeling software; i.e., Solidworks. Once the compressor was successfully "modeled" on the computer it was possible to look at each component part. From Solidworks the files were then transferred to a computer program called Mastercam - Version 9 prior to machining the parts. Since the design of the compressor is so innovative, it has been virtually impossible in the past to demonstrate to engineers and others exactly how the device works. The computer modeling done in Task 2 enabled W&W to "animate" the workings of the compressor and has proven to be invaluable as it makes the compressor dynamics more easily understood.

The unit testing performed in Task 3 identified shortcomings in both the seal system and the port geometry. First, the energized polymer seal was difficult to install between the vanes and the center ball stationary shaft and it was not possible to inspect the installation to insure a proper fit. In addition, the seal system used between the vanes and stationary components did not cover enough of the voids to prevent significant leakage between the compression and suction chambers. This greatly impacted the unit efficiency of the mechanical seal configuration. New design concepts are being investigated to achieve a more comprehensive and reliable seal between the vanes and the stationary components. The failure of the o-ring type seal at the carrier ring impacted both unit configurations; i.e., the fluid seal and the mechanical seal. However, a new seal technology has already been designed and manufactured that is expected to be much more reliable and will be applied to both configurations. As mentioned previously, performance concerns about the intake and discharge ports were also identified and addressed in this task. The time invested in working through the seal and port designs prevented the collection of comprehensive pump/compressor performance data. When these efficiency losses are eliminated, realistic performance measurement will be possible.

Even though it was not possible to gather comprehensive test data; W&W was able to bench test and to sustain 15" to 24" of hg vacuum. In short bench test runs compression output pressures ranging between 20 and 80 lbs. were achieved. These pressures were not, however, sustainable, as slippage in the seal areas generated too much heat. This issue will be further refined as our Research and Development continues.